SOLID-STATE JOINING OF MAGNESIUM SHEET TO HIGH-STRENGTH STEEL

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DOE- VTO Annual Merit Review Meeting, June 12 2019

Project ID # MAT-138

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OVERVIEW

Timeline

- Start: October 2017
- End: September 2020
- 50% Complete

Budget

- Project Funding $1.7M
- FY 2018: $525k
- FY 2019:$600k

Barriers

- “Lack of proven technology for joining dissimilar metals (Steel-Mg)”[1]
- Ability to control interfacial chemistry in order to maximize joint performance between Mg-Steel needed.

1. Light Duty workshop final report (2013) 2.1.2.2

Partners

- Pacific Northwest National Laboratory
- Oak Ridge National Laboratory

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RELEVANCE

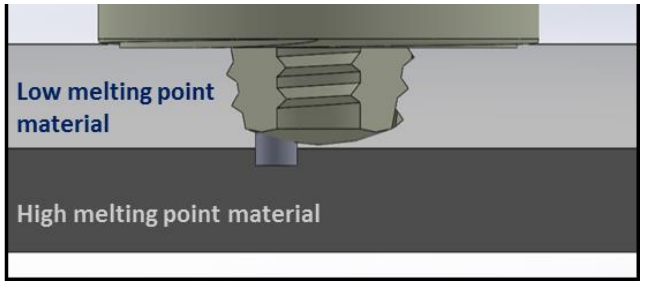
- Overall Objective
  - Mature two types of solid phase joining techniques by developing an understanding of methods and processing conditions required to achieve robust joints between Magnesium and Steel, thus integrating lightweight materials for multi-material vehicles. (Addressing barrier listed in MTT Road Map, 2017, section 4)
- FY 19 Objectives
  - Characterization and analysis of joint interface.
  - Joint fabrication in various conditions in support of modeling effort by Interface by Design (IbD) team.
- Impact
  - The knowledgebase on Mg-Steel joint interface in relation to strength, ductility and corrosion properties obtained in this project has the potential to enable widespread use of Mg-Steel joints.

MILESTONES

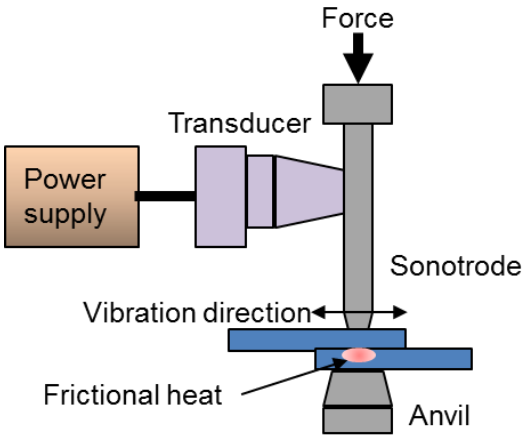
Milestone	Due Date	Status
Down-select joining techniques for investigation in FY19	September 2018	Complete
Map the mechanical properties of interfacial components (Mg-Zn-Fe) across the interface of a FSS Mg-Steel joint utilizing nano indentation techniques to provide data to the IbD task for joint performance prediction	March 2019	Complete

APPROACH

- Two solid phase joining techniques are utilized to produce Mg-Steel joints
  - Friction Stir Welding (FSW)
  - Ultra Sonic Welding (USW)
- We intend to correlate process parameters and variables to resulting interface chemistry and properties in order to tailor the joint interface that maximizes strength, ductility and corrosion resistance.
- **Magnesium Alloys**: AZ31 Sheet
- **Steel**: DP 590



Friction stir scribe
PNNL



Ultrasonic Welding
ORNL

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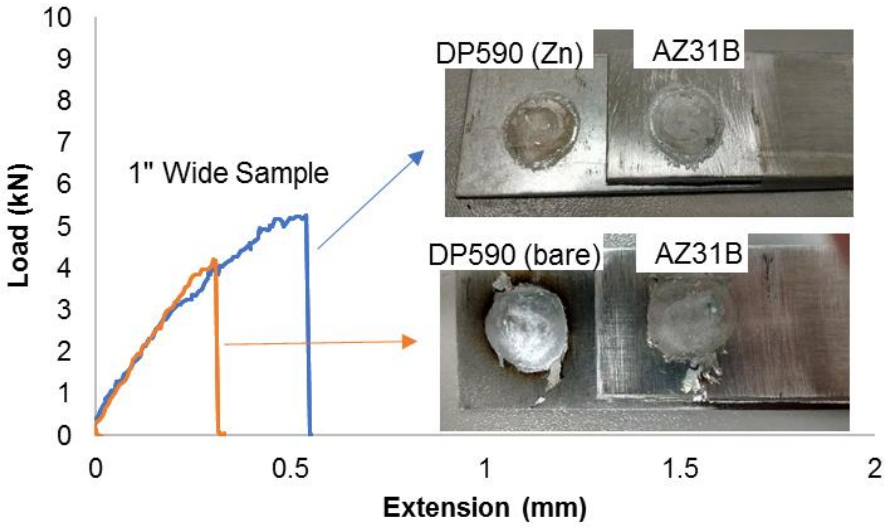
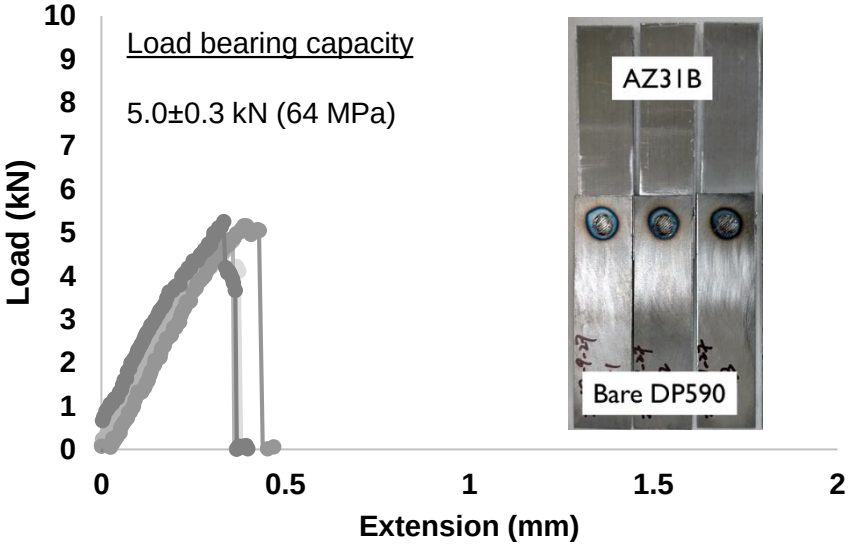
ACCOMPLISHMENTS: JOINING AZ31B (2MM) TO DP590 (1MM) BY USW (ORNL)





- Zn coated steel joints exhibited greater load bearing capacity than bare steel samples. Nevertheless the fracture mode is interfacial in both the cases.
- Increasing clamping force from 300lbf to 450 lbf resulted in stronger joints.

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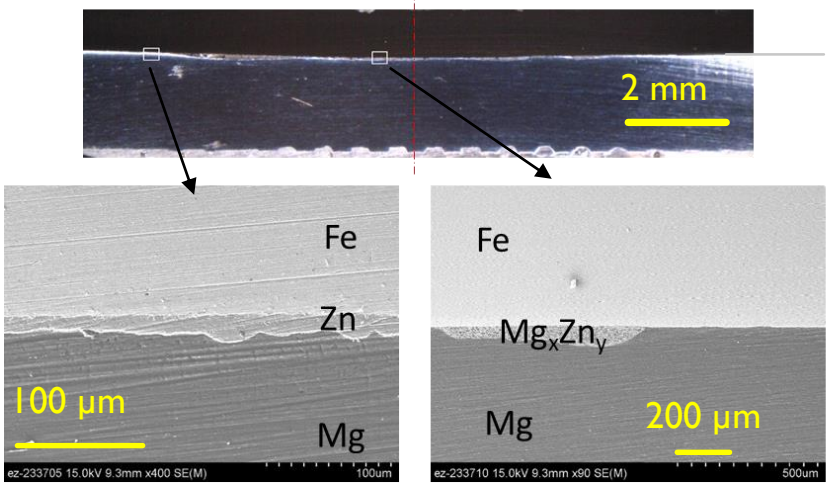
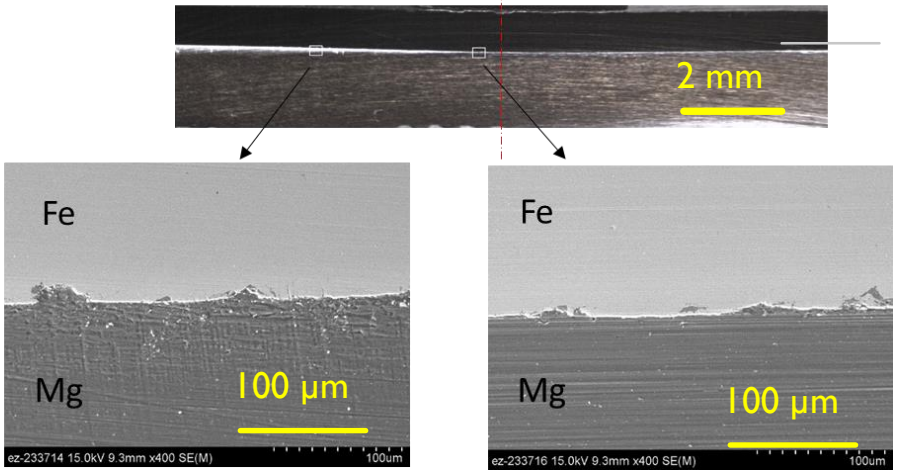
ACCOMPLISHMENTS: SEM MICROGRAPH OF USW JOINTS

Zn coated DP590 – AZ31B
Cross-section

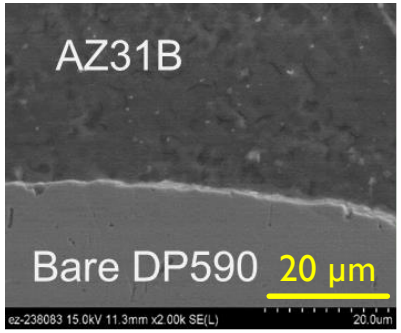


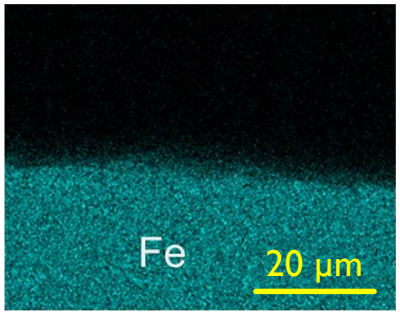
Bare coated DP590 – AZ31B
Cross-section

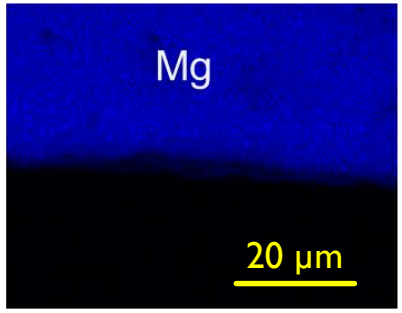


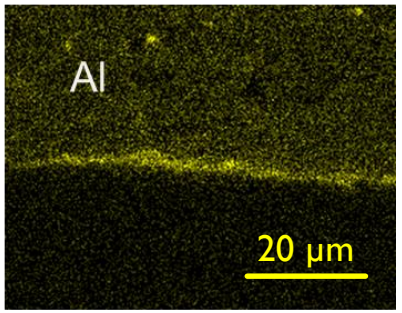
- Zn coated DP590 – AZ31B:
  - Near the center, Zn was partially squeezed out and the remaining Zn formed Mg_xZn_y intermetallic (50~80µm thick)
  - Near the edge, no presence of intermetallic
- Bare DP590 – AZ31B:
  - While bonding is observed between Mg/steel, detailed investigation of the bonding mechanism is on-going.

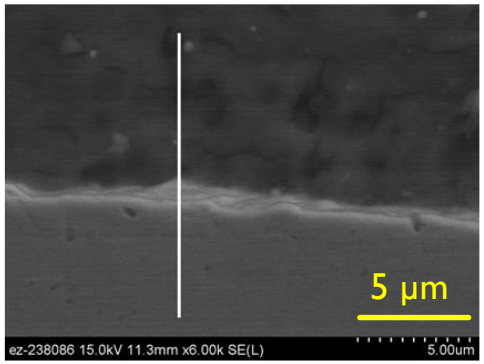
ACCOMPLISHMENTS: EDX ANALYSIS ON BARE DP590 AND AZ31B JOINTS

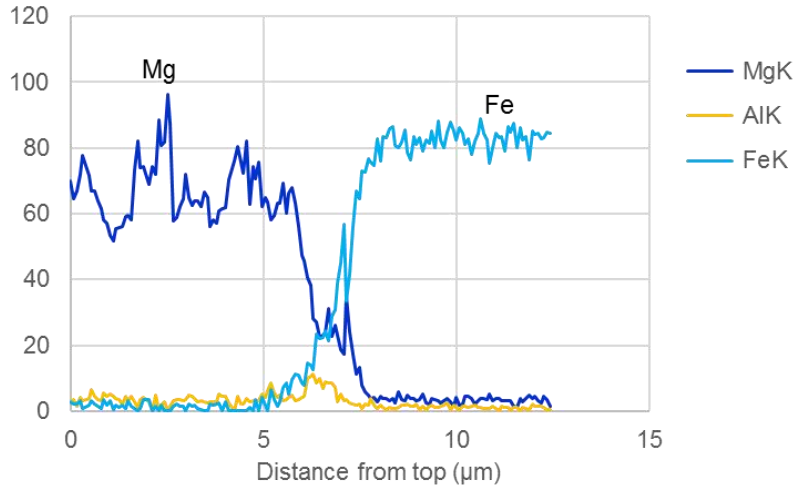






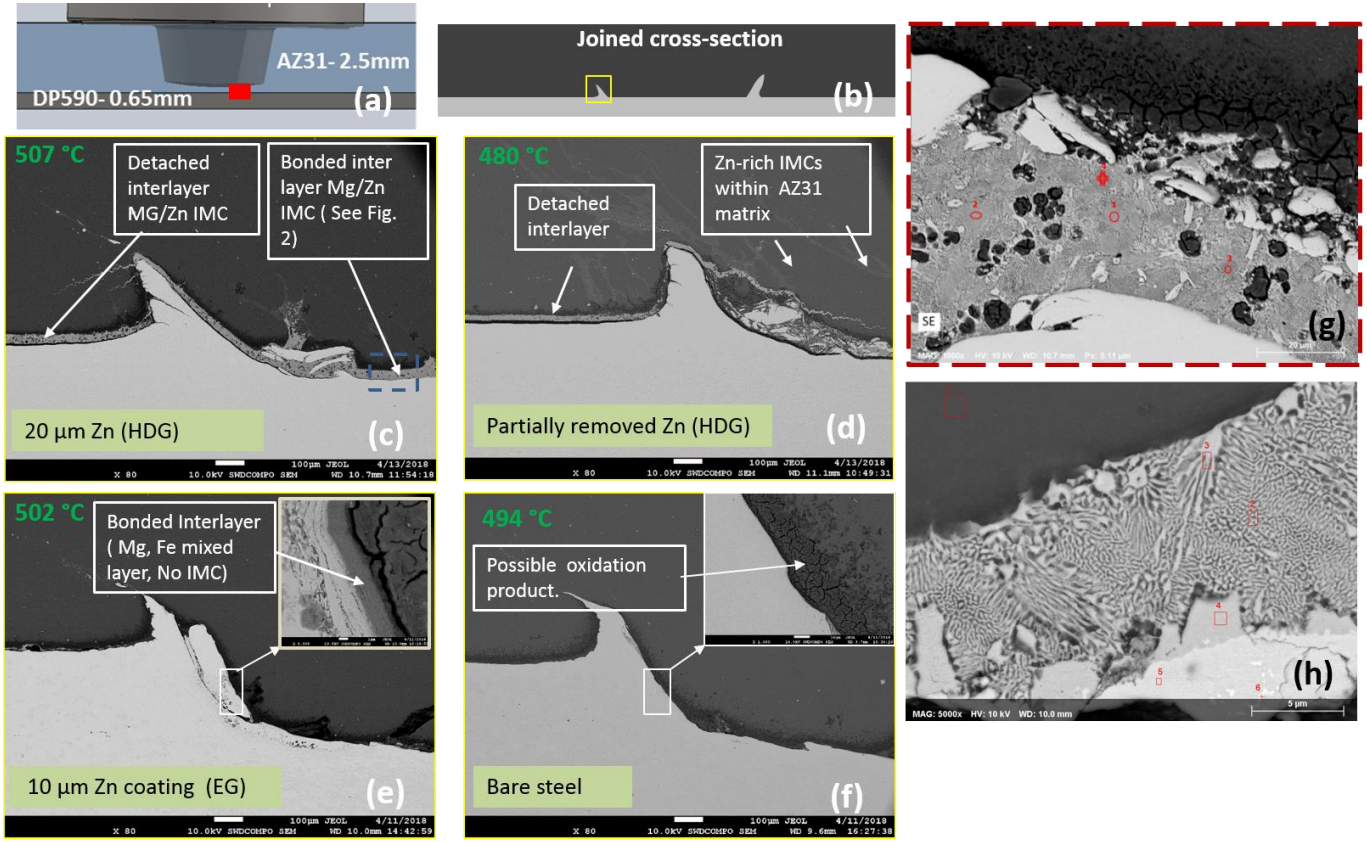






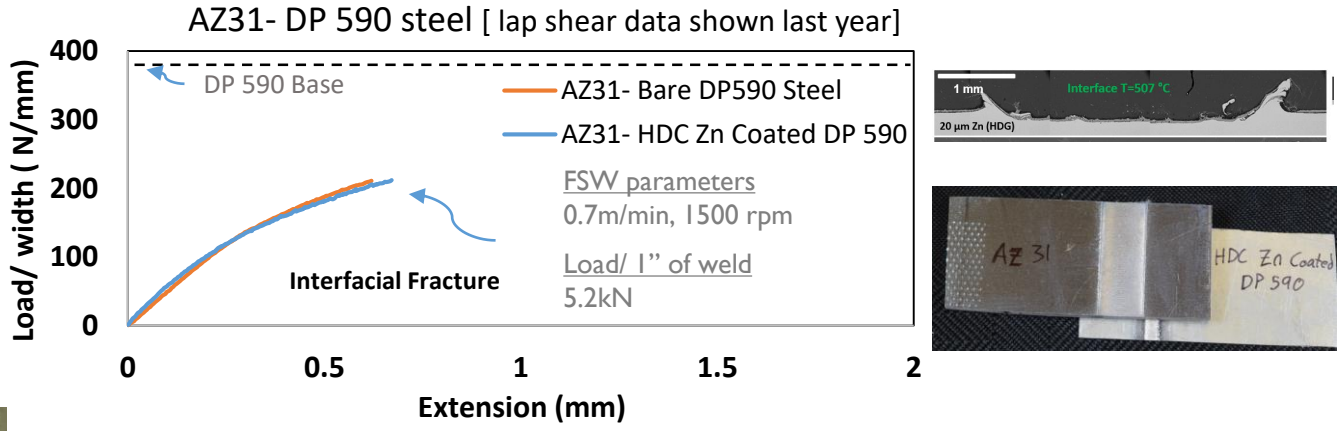
- EDX confirmed that Zn coating was completely removed.
- Slightly greater concentration of Al (one of the AZ31B alloying elements) at the interface was observed.

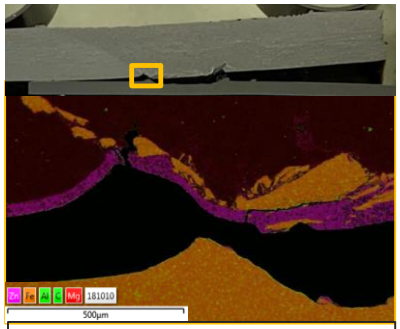
CROSS-SECTION FOR FSW SCRIBE JOINTS



- IMC layer consisting of Mg/Zn eutectics are observed between Mg/steel interface.
- Interface ranges from 25µm to 10µm and is dependent upon Zn coating thickness.

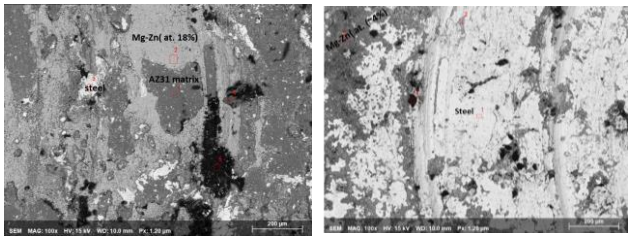
ACCOMPLISHMENTS:
Fracture mode and surfaces (FSW scribe joints)





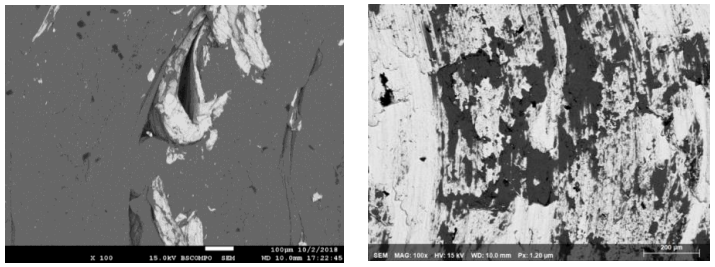
Fractured Cross-section

AZ31 side | HDG DP590 side



(Zn coated steel-Fractured surface)

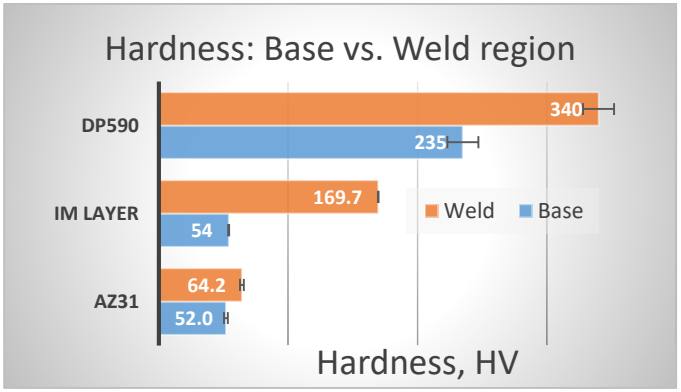
AZ31 side | HDG DP590 side

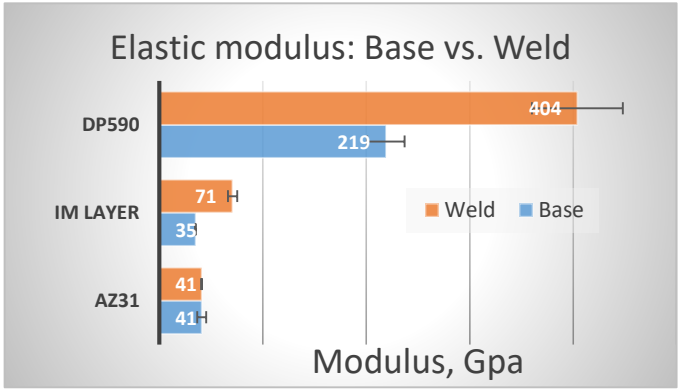


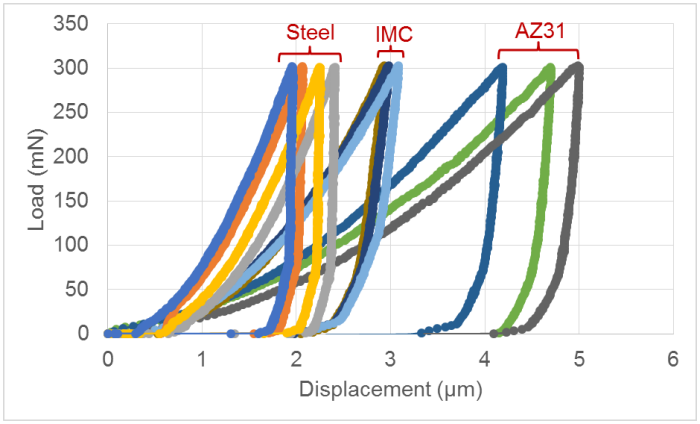
(Bare steel fractured surface)

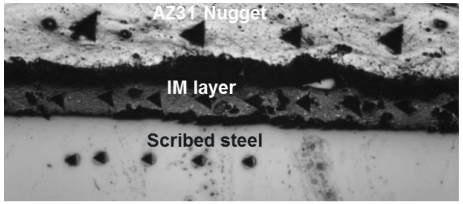
- Joints made has resulted in joint strength corresponding to ~68MPa (in lap shear) (based on estimated bond area).
- Fracture takes place at the interface of Zn/Mg Eutectic/ IM layer and Steel. Some Eutectic layer is attached to steel. Hooks/stray steel fragments also break into the mg sheet.

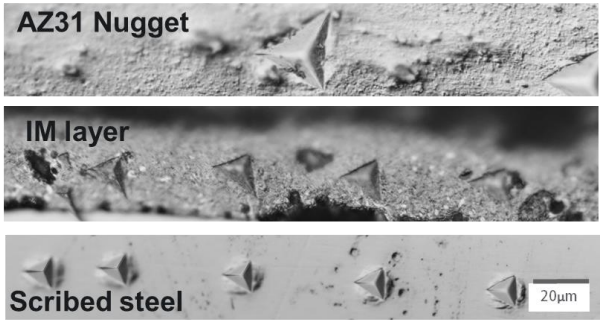
ACCOMPLISHMENTS: IMC LAYER CHARACTERIZATION







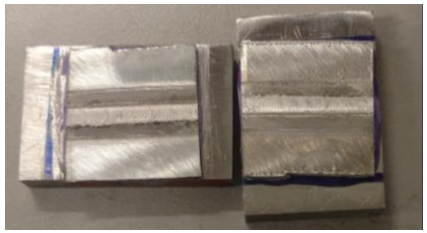


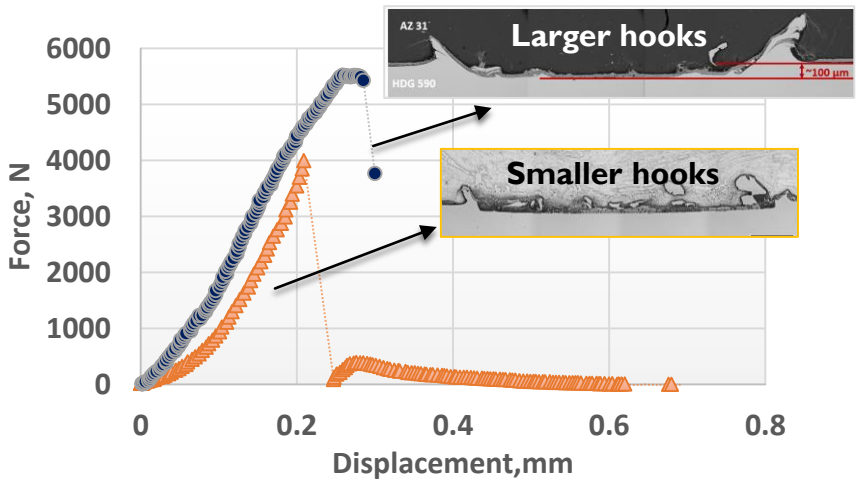


- We saw a significant increase in hardness (plastic property) and elastic modulus in IM layer between Mg/steel at the weld interface compared to outside of the hook region.
- Dataset like this will be utilized as input parameter by IbD.

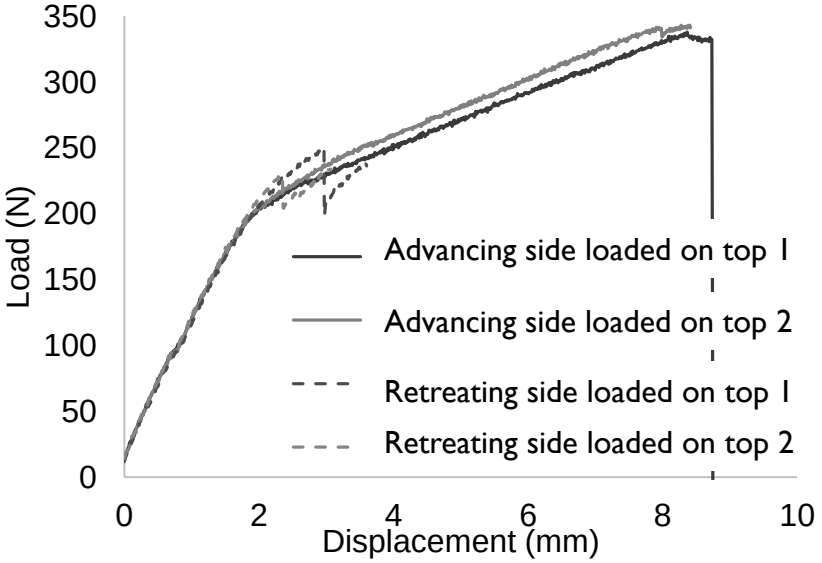
ACCOMPLISHMENT: TESTING TO CHARACTERIZE JOINTS IN SUPPORT OF MODELING

Cross Tension



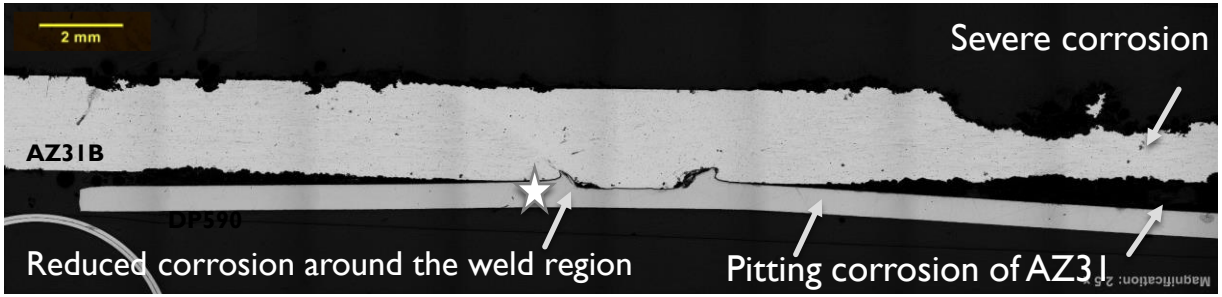


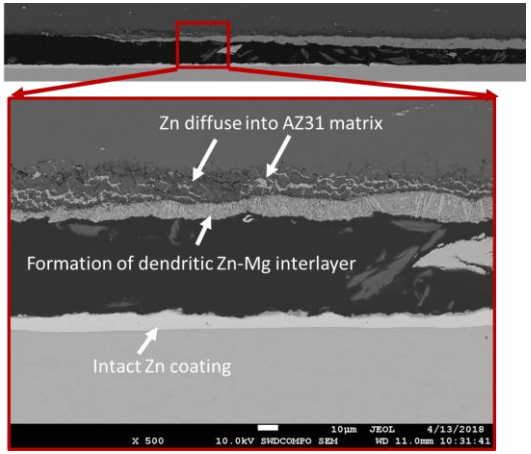
T peel test



- Cross tension and T peel tests are being performed to characterize the joints.
- Hook size effects in the tension tests, and advancing vs. retreating side effect on the peel test is seen preliminary data shown above

ACCOMPLISHMENTS: CORROSION CHARACTERISTICS STUDY





Cross-section just outside of the hook region

Fracture joint surface shows region with reduced corrosion activity (24 hours under salt fog B117)

- We observe reduced corrosion activity underneath the weld region.
- Zn-Mg eutectic may be forming a barrier to corrosion in AZ31.
- Lap shear strength was unchanged despite corrosion with 24 hours of B117 exposure.

RESPONSES TO PREVIOUS YEARS REVIEWERS' COMMENTS

- Reviewer: Why was Al- steel interface not selected? Is correlation of process parameters to interface chemistry guaranteed? How is the test behavior being used by modeling team?
  - Response: The scope of the project is specific to Mg and steel interface as joining in this combination is not as well understood as Al/steel joints especially because of no solubility of Iron in Mg. While some correlation can become apparent with parameters, we are looking at process conditions like temperature to assess interface chemistry. The test behavior will be used directly by modeling team to obtain cohesive parameters.
- The reviewer expected that the team will evaluate a number of failure modes, including TSS, CTS and/or t-peel, which would increase confidence in the process. Additionally, the reviewer said that there should be a stretch joint, i.e., considering Mg to a UHSS of at least 980 MPa.
  - CTS, T peel are currently being evaluated.
  - DP590 is the candidate steel for the project. We have not looked at UHSS steels yet.
- Reviewer : Role of each lab is the role of each party is not very clear.
  - PNNL is taking the lead on Friction stir approach of making the Mg/steel joint while ORNL is utilizing ultrasonic welding for making the joint.
- Several reviewers stressed the need for industry participation
  - Because of the early stage (low TRL) level of the joining core program (JCP) , we are currently not working directly with the industry. The aim is to leverage the knowledgebase obtained from JCP and apply it to specific projects in association with commercial partner separately.

COLLABORATION AND COORDINATION

- Modelling and Experimental teams from both the labs are working together in this project.
- Meetings between the different teams help facilitate sharing of information and feedback on results and upcoming tasks.
- Results of this project will be disseminated through journal publications, conference presentations.

Core Research Team

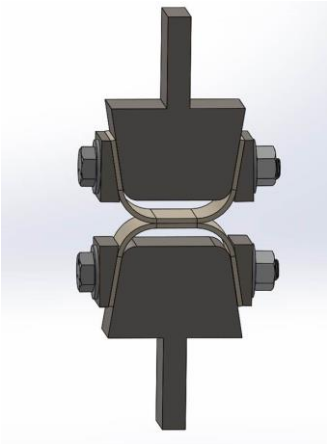
- ORNL: Zhili Feng, Jian Chen, Yong Chae Lim, Hui Huang
- PNNL: Piyush Upadhyay, Tianhao Wang, Darrell Herling, Xiujuan Hellen Jiang, Wenbin Kuang, Tim Roosendaal

REMAINING CHALLENGES AND BARRIERS

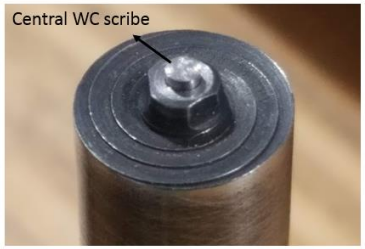
- Mechanical properties of intermetallic layer and its bond strength to steel substrate needs to be determined for accurate modeling.
- Verification test for cohesive zone model: U peel samples test fixture needs to be implemented.
- Joining mechanism of bare steel to AZ31B made by USW needs to be investigated.

PROPOSED FUTURE WORK

- Complete interface characterization of developed joints in welding conditions including phase identification.
- Complete instrumented experiments to validate predictive model in coordination with “interface by design” project.
- Carry out joining runs to establish hook size and shape correlation with welding parameters.



U peel test fixture



Large central scribe

W-C pin tool

Any proposed future work is subject to change based on funding levels

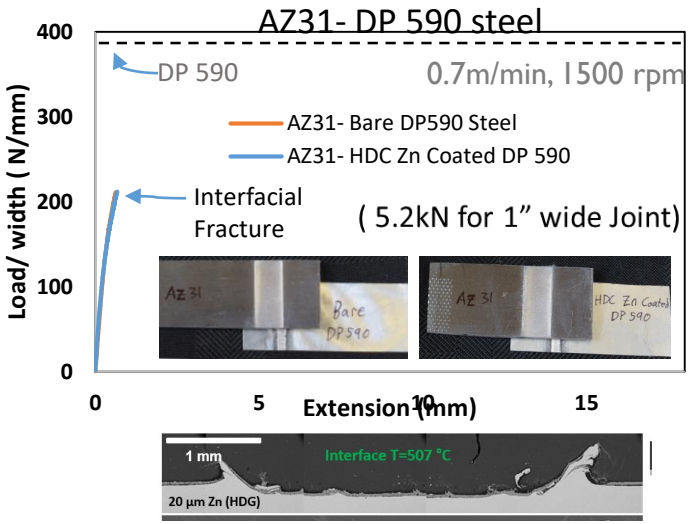
SUMMARY

The goal is to develop an applied understanding of localized metal forming and associated metallurgical bonding in Magnesium to Steel joint. By utilizing several advanced characterization techniques, we intend to correlate processing parameters and variables to resulting chemistry and properties in order to tailor the joint interface that maximizes strength, ductility and corrosion resistance.

- This year we made progress in interface characterization and understanding fracture mode in Mg/steel joints.
- Joint line disruption processes resulted in joint strength of 5.2kN/ 25.4mm joint.(~54% joint efficiency for DP590). Mixed interface layer found in this joints are being investigated. USW process has resulted in lap shear strength of ~3.3kN/25.4mm.
- Series of tests are being carried out in support of IbD team to supply dataset predictive capability.

TECHNICAL BACKUP SLIDES

Mechanical Test results (Scribe)



- A load bearing capacity of ~ 5.2kN/1" wide joint was observed regardless of fracture mode. (with and without Zn coating)
- Load carrying capacity for both the joints are similar: Is the strength coming from interface or hooks?
- **Need to Decouple** (interface bonding vs. mechanical bonding)

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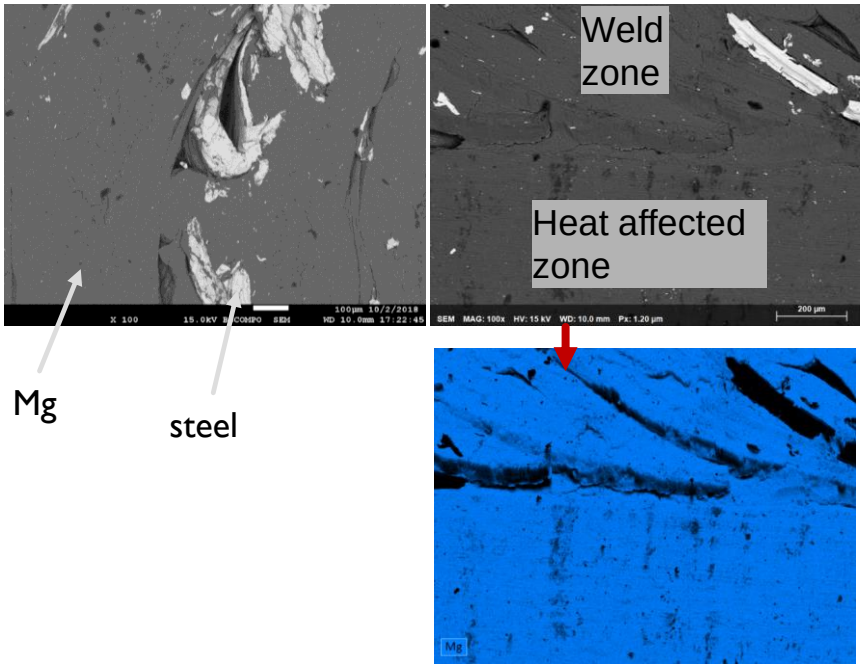
FRACTURED SURFACES: BARE STEEL

Mg side

weld zone

Transition region

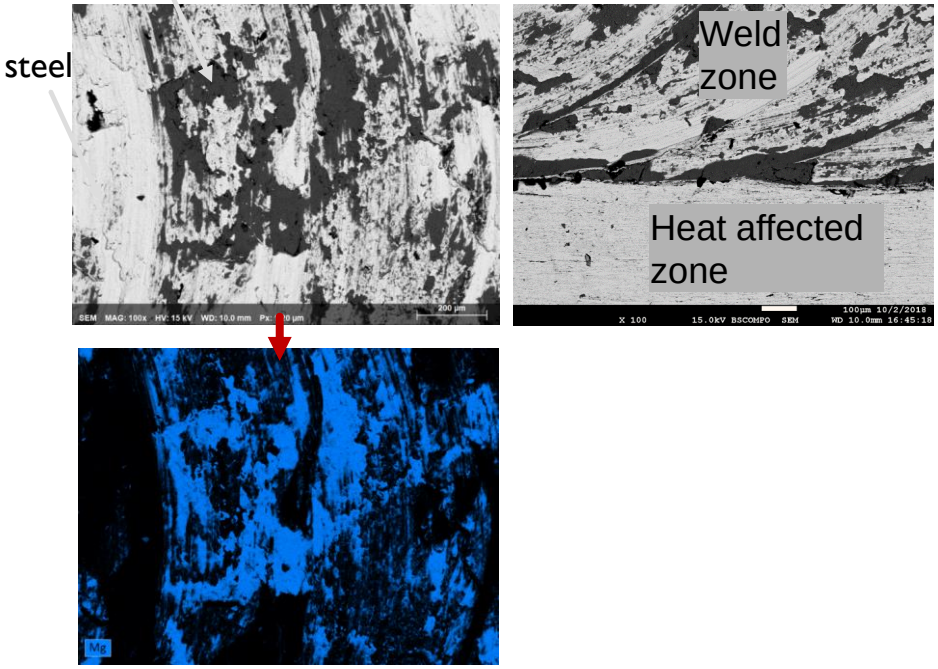


Steel side

Mg

Weld zone

Transition region



- Steel side: a portion of Mg matrix is stuck. Indicates intermittent Mg fracture.
- Mg side: Some steel debris along the FSW flow lines.

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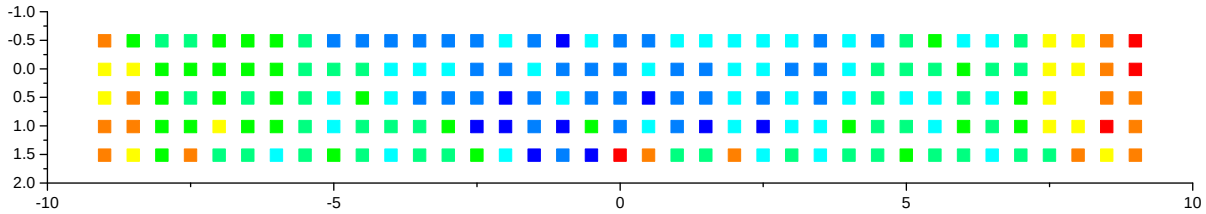
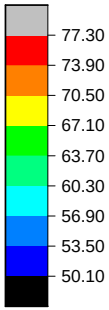
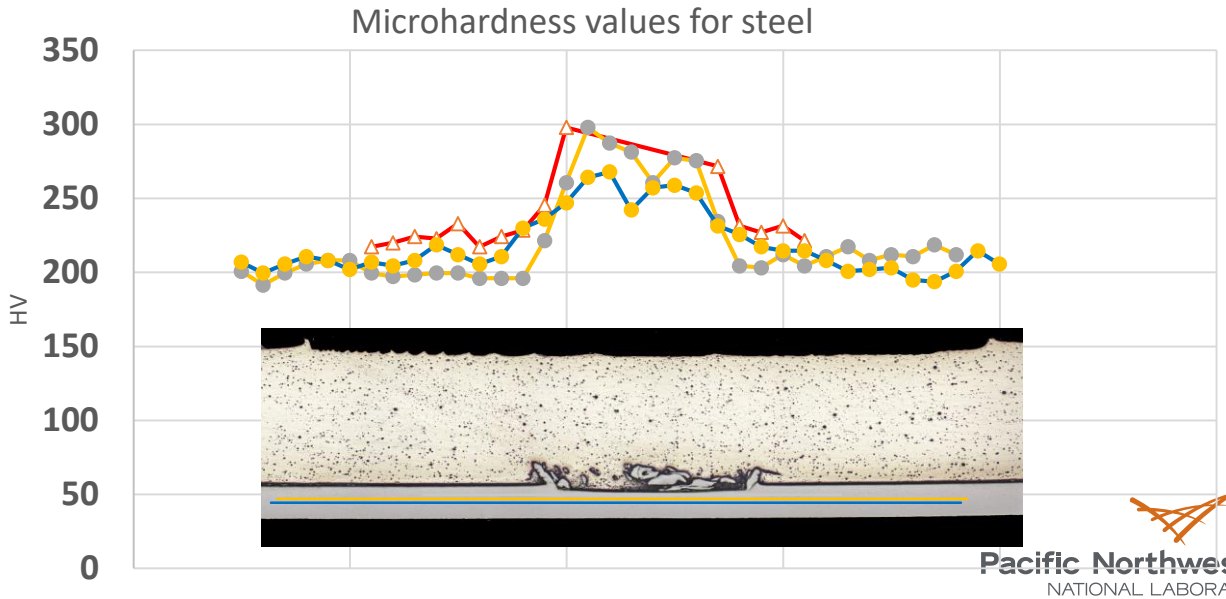
HARDNESS DISTRIBUTIONS



AZ31 scribe weld region





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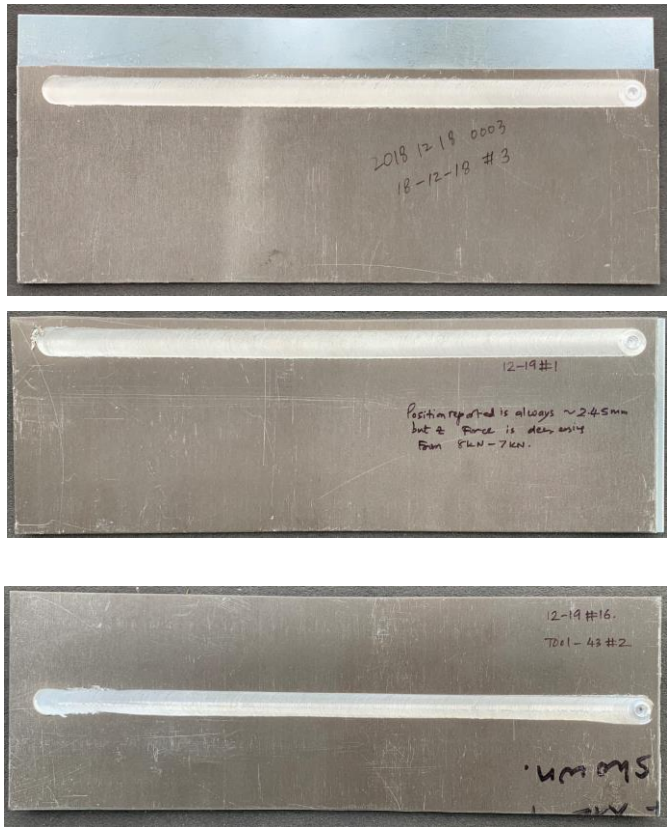
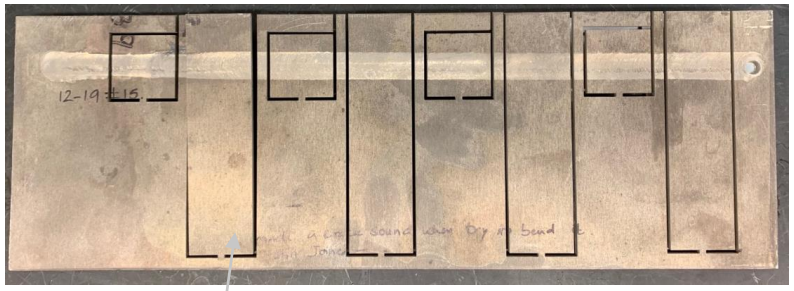
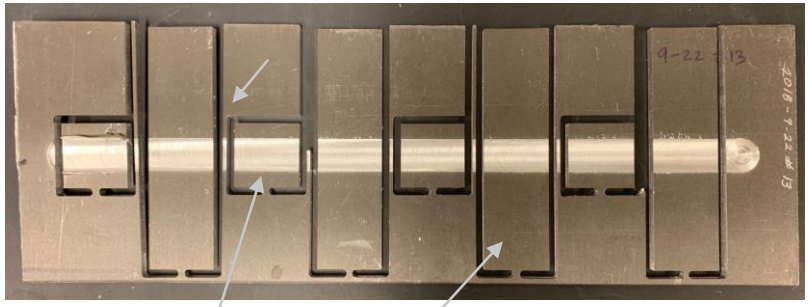
EXAMPLE WELDED JOINTS AND CUT SAMPLES





T peel sample



Cross tension samples

U peel sample

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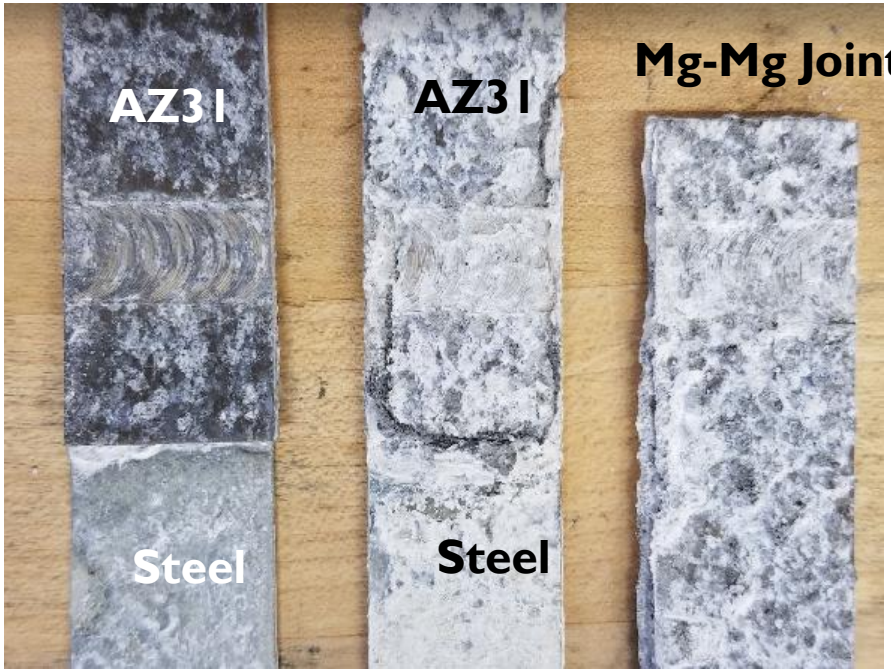
ASTM B117 SALT FOG TEST

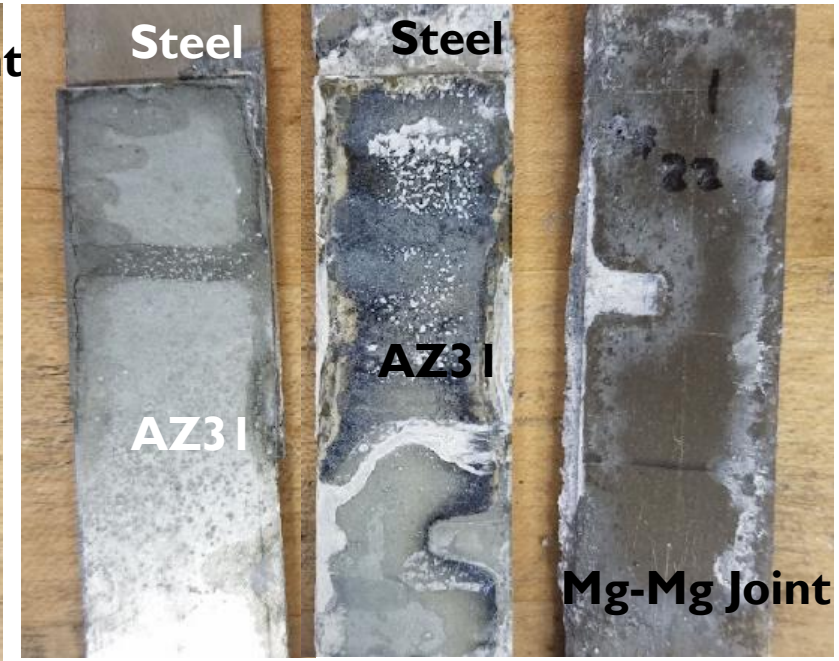
As welded

Front side



24 hours | 72 hours | 72 hours

Back Side



24 hours | 72 hours | 72 hours

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